THE EFFECTS OF URBAN POLLUTION UPON A CORAL REEF SYSTEM

A PRELIMINARY REPORT

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PREFACE

We. the authors, are presenting this preliminary paper on the changes in the benthic biota in Kaneohe Bay because of the urgency of community planning. Our subjective and roughly quantified survey of the reefs, together with a review of previous biological studies of the Bay, have shown that profound changes have occurred in the bottom flora and fauna. We present evidence to show that these changes are probably resultant from population growth and its concomitant land development in the Kaneohe Bay watershed: the eutrophication of the Bay from sewage discharge and the combined siltation and lowered salinity in times of storm.

At this moment of writing, the city, county and state officials, as well as citizen's community groups are concerning themselves about the relocation of sewer outfalls and more stringent control of land development. We wish this summation of present conditions in Kaneohe Bay to be available to them.

Plainly this is a preliminary study. We plan to seek answers to many of the scientific questions that this paper raises during the coming year in a more exhaustive study under special research funds granted by the Honorable John A. Burns, Governor, State of Hawaii.

ABSTRACT

In a review of previous work it is shown that Kaneohe Bay, Oahu, has a rather restricted pattern of circulation and that in recent years a number of changes have occurred in the Bay waters which include increased siltation, at times great lowering of salinity, a many-fold increase in phosphates, and great changes in the plankton community. Data is adduced to show that these changes parallel the growth of population in the watershed, especially in the southern section, and in particular parallel the development of new subdivisions that permit a greater runoff of silt from land and the operation of two sewage systems that discharge into the southern pocket of the Bay. Attention is called to the reports of coral growth in the pristine waters of the Bay almost a half century ago. The results of a diving survey of 155 reef areas, covering all areas of the Bay are reported: the reefs of the southern sector of the Bay are virtually devoid of living coral; the reefs of the middle sector have the once dominant coral being invaded, killed and decalcified by the alga, Dictyosphaeria cavernosa; *only the reefs of the northern sector and outer waters of the Bay seemingly are still unaffected. It is suggested that the parallel in time and geography between the urban pollution of the Bay and the alteration of the ecosystem, including the death of the coral, is too great to be other than a cause-and-effect phenomenon.*

INTRODUCTION

Kaneohe Bay lies on the northeastern side of Oahu, approximately 12 miles[1] by highway from downtown Honolulu. The Bay is 7.9 statute miles long, 2.6 miles broad at its center and 62' at its greatest depth (Map 1, p. 3). The depths in the southern section and "lagoon" behind the "barrier reef" usually run from 40 to 50 feet. Surrounding all margins of the Bay, and scattered throughout the Bay are--or were--living coral reefs. The broad front of the Bay, facing the prevailing trade winds, is largely occluded by a system of shoals, similar to a barrier reef. The present scattered and sparse coral growth on the reef would not be adequate to account for the barrier formation. The barrier system carries two small islands, Kapapa and Kekepa, both of which are fossilized sand dunes (Chave, personal communication). The barrier is broken by only two passes, the Sampan Channel to the south with a minimal depth of about 8 feet, and a Ship Channel to the north which was broader and deeper under natural conditions and has been dredged to the depth of 32 feet.

The Bay may be divided into three sectors. In the south is a broad, relatively deep basin that is cut off from the full Bay circulation by a shoreside point, Coconut Island (Moku-o-loe) and an extensive shoal reef system to the northeast of the island. The middle sector is

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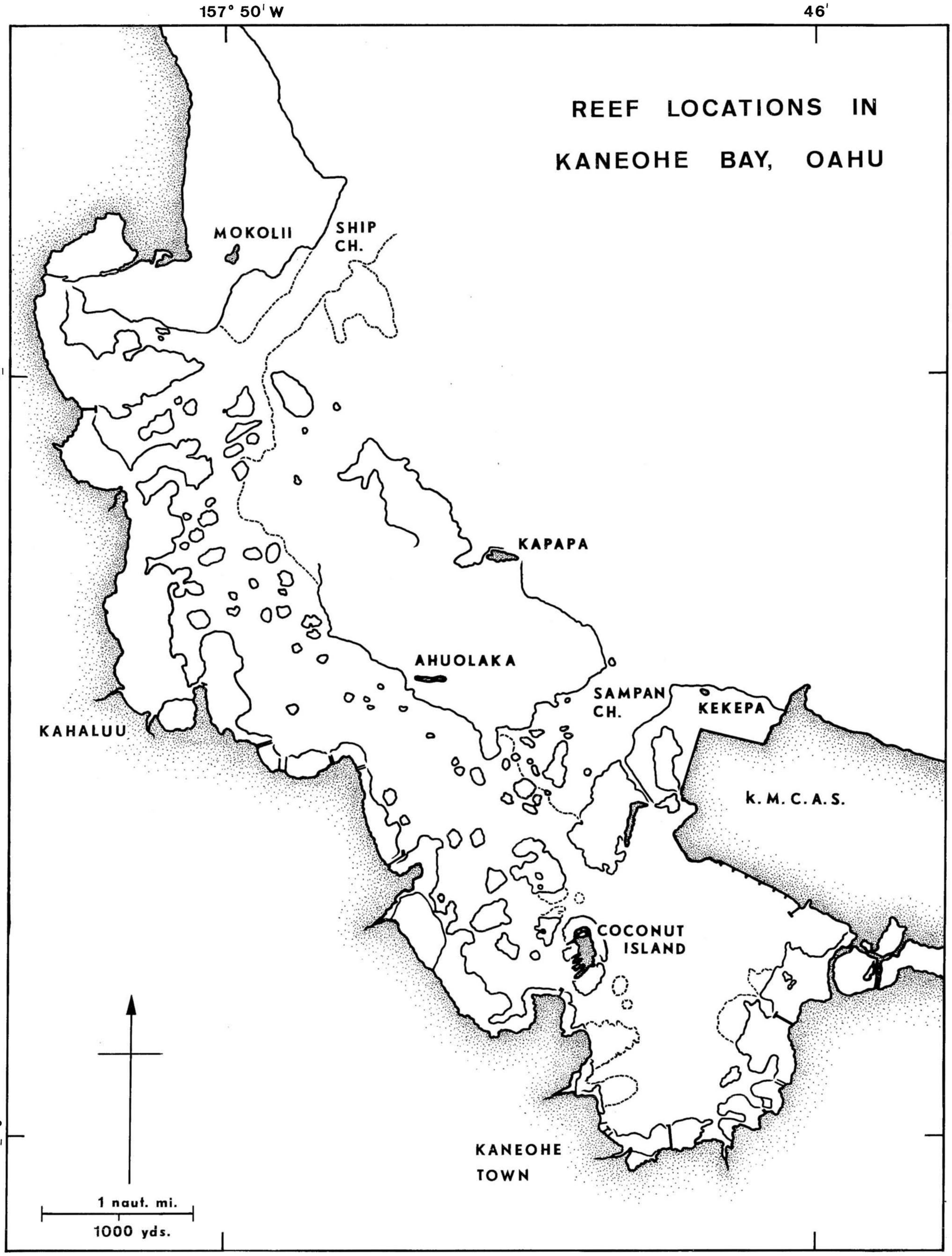
[1]Except for chemical measurements, English measure will be used in this study to make it more available to community planners.



MAP I. Reef Locations in Kaneohe Bay. K. M. C. A. S. is the Kaneohe Marine Corps Air Station; dotted line represents reef areas below 10 feet; solid reef lines represent reefs at or near surface. Adapted from U. S. C. & G. S. Chart 4134 and aerial photographs.

characterized by the lagoon lying behind the barrier reef system; it contains numerous patch reefs. The bottom of the southern basin and central lagoon in deeper water is of thick, soft mud. The barrier reef in the northern sector is deeper and less well defined and the bottom is more shoal and mostly covered with rubble. In the northern sector there are less shoal patch reefs, and the shoreside reef system becomes less well defined, almost entirely disappearing as muddy shoals in the northwest corner.

Bathen (1968) carried on extensive studies on the hydrology of the Bay. He showed that with both flooding and ebbing tides under normal trade wind conditions there was a net transport of water inward across the barrier reef front (Maps II, III, pp. 5,6). On ebbing tides, the water escapes through both channels, but in the deeper portions of the Ship Channel there is a small outward transport even on rising tides. He reports that there was a net outward transport of 12.9 x 10^6 m^3/day through the Sampan Channel, and 18.5 x 10^6 m^3/day through the Ship Channel. Most of this net outflow was water that came into the Bay over the barrier reef; he estimates that only 0.3 x 10^6 m^3/day was added to the Bay by streams and sewage. He reports that there is a transport of water northward along the lagoon, particularly on falling tides. He devotes special attention to the southern basin, where there are relatively slight currents and a low exchange. Gray and Lau (Draft Report)[2] in a recapitulation of Bathen's work, state: "The

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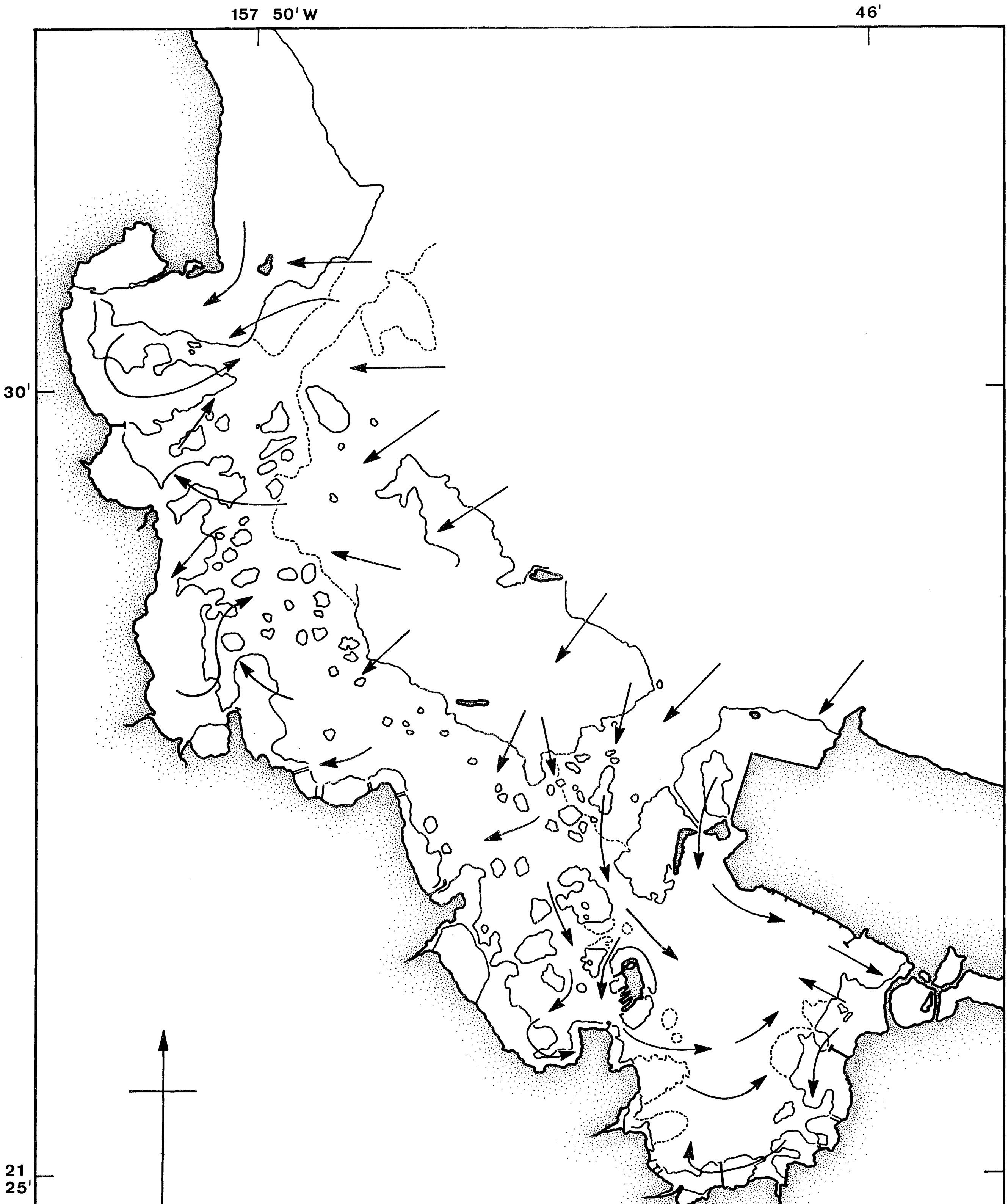
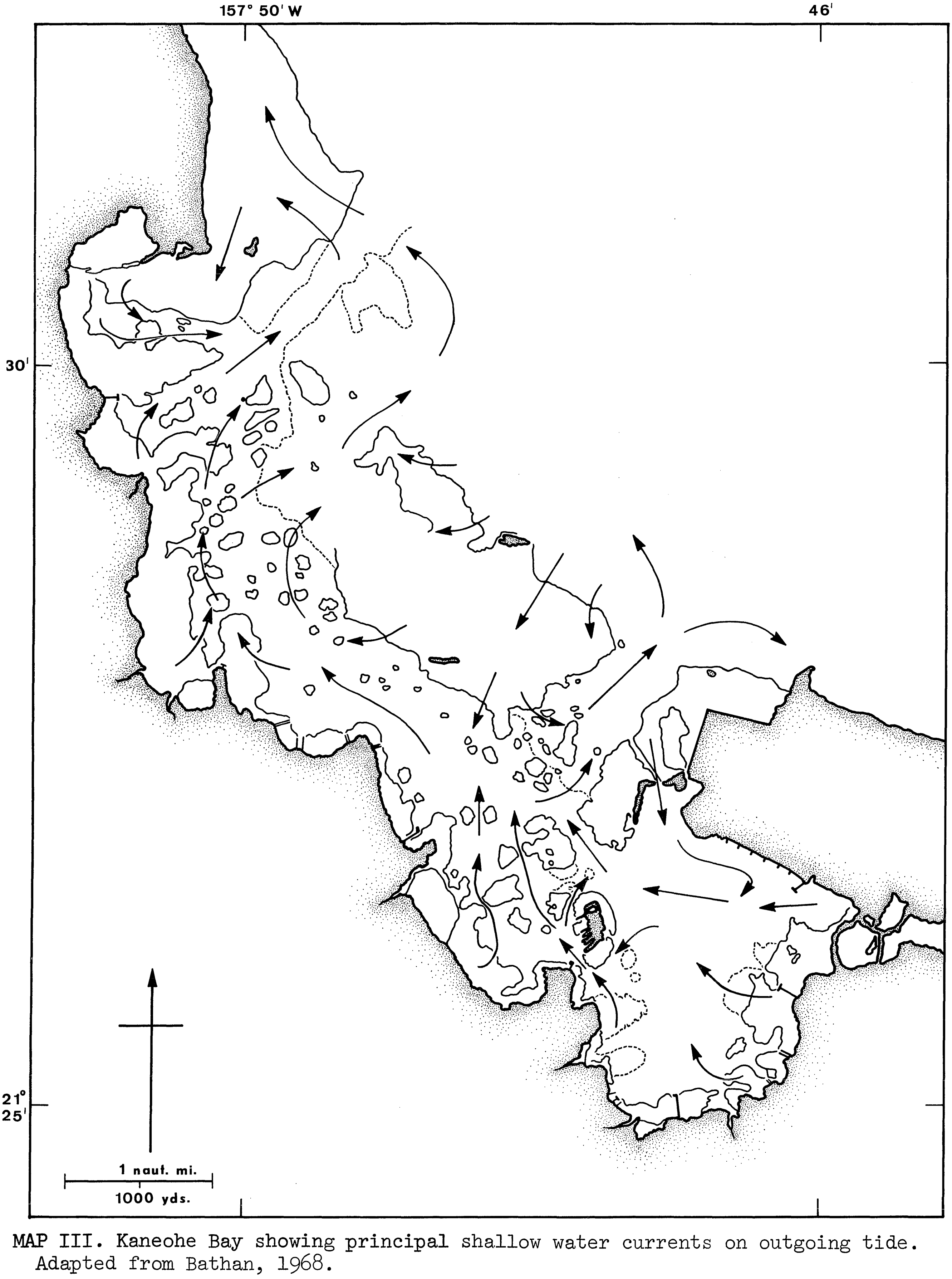
[2]See note on Draft Reports in bibliography.



MAP II. Kaneohe Bay showing principal shallow water currents on incoming tide. Adapted from Bathan, 1968.



MAP III. Kaneohe Bay showing principal shallow water currents on outgoing tide. Adapted from Bathan, 1968.

southeast [=southern] basin has 27 percent of the total Bay volume, yet it receives only approximately 8 percent of the total exchange transport in and out of the Bay. . . . The daily exchange is . . . about 0.4 percent of the total basin volume per day, as compared with the daily exchange transportation of the total basin [=Kaneohe Bay] of . . . 26 percent of the basin volume."

Bathen also pointed out how slowly the net transport accomplished the flushing of Bay waters. He divided the Bay into two halves, approximately through the sand bar, Ahuolaka. The northern half, being more shoal and having two-thirds of the channel cross-sectional area, has the greater flushing rates; the southern half is markedly more sluggish. "The consequences of this is that 2 to 4 tidal changes (approximately 15 to 20 hours) were necessary for a sudden sewage discharge in the southeast basin to leave the southern half of the bay." He estimated that it took an average of 4.8 days for each cubic meter of sewage to be flushed from the Bay. He also pointed out that the currents and the flushing rate varies widely, depending upon the strength and direction of the winds.

No quantitative information can be obtained on the growth of corals in the pre-pollution period of Kaneohe Bay. In 1915 MacKay (evidently a trained zoologist who could identify corals from Vaughn's work) wrote: "Probably no other one spot in the Territory of Hawaii can show such wonderful variety of corals as the waters of Kaneohe Bay and the surrounding reefs on Windward Oahu . . . . Considerably over one hundred varieties of corals are known to exist in Kaneohe Bay where lie the famous Coral Gardens, the sheltered formation of encircling shores being advantageous to the propagation of nearly all the species inhabiting the Hawaiian waters." Later in the article is mentioned the Coral Garden Hotel and its glass-bottom boats for viewing the coral. The Coral Garden Hotel was located in the southwestern corner of the Bay, adjacent to the two dredged reefs (indicated by dotted lines on Map I).

Thirteen years later Edmondson wrote in his paper on ecology of Hawaiian corals (1928): "Kaneohe Bay, on the windward coast, is recognized as one of the most favorable localities for the development of shallow water coral. Nearly all the reef-forming genera known in Hawaiian waters are represented . . . and many species grow luxuriantly."

When the senior author moved his home to Kaneohe Bay in 1951, conditions were still quite like those described above for the middle bay region. The vigorous shoreside reefs and the larger patch reefs were of similar form. The reef flat was of sand, or along some of the shores, of sandy silt; the surface was partially exposed on spring tides. Along the edge of the flat was a band of living coral 10 to 30 or more feet wide; the individual heads were dead on their tops where they were exposed on maximal spring tides, but were growing laterally. Back from the reef front the heads became scattered, but the edge itself was a solid rampart of living coral. Healthy growing coral extended down the steep outer face of the reef front to depths of 15 to more than 30 feet, depending upon the clarity of the water.

The senior author has only hazy recollection of the coral growth on the shoreside reefs of the southern section of the Bay, the area mentioned by MacKay in 1915. However, his recollection does not include the extensive coral stands implied by MacKay. The coral in front of the old Coral Gardens Hotel site was dredged by the U. S. Navy prior to, or during, World War II. However, the author does recall firmly the conditions on a patch reef immediately south of Coconut Island (our Station 137 on Map IV, p.35). This reef also had been dredged to about 10 feet by the Navy. The middle part of the reef surface was covered with sand and had only scattered heads of coral, but the margins were solidly covered by growing corals, mostly *Porites compressa* Vaughan and *Montipora verrucosa* (Lamark).

In the outer portions and northern sector of the Bay the patterns of coral growth and reef formation differed, apparently because of wave action. In these areas where reefs occurred, they did not reach the surface and much of the area was rubble bottom with only scattered heads of coral, and often brown algae of various genera.

The species making up the bulk of the coral on the inner and middle reefs were limited. *P. compressa* was by far the dominant coral, with *M. verrucosa* the coral second in importance, contributing but little to the bulk of the reef. In certain areas *Pocillopora damicornis* (L.) was not uncommon, and *Fungia scutaria* Lamark was found near the reef edges. Deeper and in shaded areas was *Tubastrea aurea* (Quoy and Gaimard).

In the outer and more northern sections of the Bay where wave action was greater, the massive *Porites lobata* (Dana) and *P. evermanni* Vaughan and other corals occurred; both in the middle bay where wave action was strong, and at the ends of the ends of the channels, and in the outer bay the two species of *Pocillopora, P. meandrina var. nobilis Verrill,* and *P. ligulata* Dana were common.

Many other species of corals occurred in the Bay and along its outer face, but except for restricted areas, none were as abundant or dominant.

CHANGES IN KANEOHE BAY

Urbanization of the Kaneohe Drainage System

The period from 1950 to 1970 marked the change of Kaneohe Bay watershed from an agricultural community to a suburban community. United States census figures for Kaneohe Town, at the south end of the Bay, are given in Table 1.

TABLE 1

GROWTH IN KANEOHE TOWN, 1940-1970
(Taken from the U. S. Census)

1940	1950	1960	1970
1,762	3,208	14,414	29,405

Crowding in Honolulu itself, the development of high-speed freeways and the extensive use of the automobile for commuting caused many subdivisions to be developed on the previously agricultural land in the district, first adjacent to the southern Bay, and then gradually reaching northward towards the middle of the Kaneohe Bay watershed. For these subdivisions pasture land was destroyed, old rice and taro ponds were obliterated, hillsides were bulldozed for house lots, storm sewers were installed to lead directly to the bay or indirectly through "improved" streams that were lined with concrete. The original rural cesspool system was replaced by a secondary sewage treatment plant that was opened by the City and County government in 1962.

The urbanization, or more properly, sub-urbanization, of the area has brought no major industries with deleterious waste discharges. There is no major shipping in Kaneohe Bay except for the U. S. Navy transports that occasionally visit the Kaneohe Marine Corps Air Station (KMCAS on Map I). The only major commercial fishing are the tuna boats that enter the bay to capture baitfish. All other boating is that of small pleasure craft, both power and sail. To our knowledge, there are no individuals living permanently upon small craft within the Bay.

Land Runoff

With the removal of natural vegetation and the destruction of dyked paddies, with the bulldozing and laying bare of hillsides, with the increased areas of impervious surfaces as in roofs, streets, and large parking lots, and with the concrete channeling of streams, more of the water from violent rainstorms flows into the bay, and flows in more rapidly. Banner (1968) records such a rainfall and its results upon the reef. During the first nine days of May, 1965, three rain gauges in the southern Kaneohe Bay area recorded totals of 31.06, 17.98, and 24.13 inches of rain. On May 2, the rainiest day, the twenty-four hour totals were 21.16, 10.52, and 17.16 inches. Some of this rain fell directly on the bay, but the thickness of the observed layer of brackish water floating on the more saline greatly exceeded the total rainfall for the only rain gauge actually on the Bay, that of Coconut Island (the middle figures above). He recorded deaths of coral along the various reef fronts in the center and southern section of the bay ranging from 0.0 to 3.0 and 5.0 feet below the previously growing top of the reef. He also recorded deaths of many species of invertebrates and fish. He believed that the death of the coral was from three factors: the lowering of salinity in the upper strata of the Bay's waters, the silting from land runoff, and the lowered oxygen tensions in the water due to death and decomposition of the marine biota. How much of the blame for the coral death can be placed upon urbanization, and how much of the coral would have died had the rain storm fallen on agricultural lands could not be determined.

Sedimentation

Sediment in the Bay's waters is from four sources: terrestrial erosion, as discussed above under land runoff, reef erosion under the influence of waves on the reef flats, marine dredging operations, and organic sediments from the biota in the water mass above. The effects of terrestrial erosion are the most conspicuous: after a storm, whole sections of the Bay are deeply stained with red dirt from stream runoff. Banner (*loc. cit.*) reports that the day after the maximal rain in 1965, an extremely turbid layer existed in the lagoon at Coconut Island to the depth of four or five feet, and eight days after the storm maximum Secchi disk readings gave extinction at depths of 4.7 to 5.7 feet in the southern sector of the Bay. The only direct reading of the sediment carried by a stream under storm conditions is that presented by Fan and Burnett (Draft Report). The storm was that of 1 February 1969 when two rain gauges in the southern drainage section of Kaneohe Bay registered 1.90 and 2.40 inches, and the Coconut Island gauge registered 3.50 inches. The authors sampled Kamooalii Stream which flows into the southwestern corner of Kaneohe Bay and projected from their samples that the discharge from that single day "probably consisted of 2,178 tons of sand, 4,072 tons of silt and 3,220 tons of clay", a total discharge of 9,470 tons of sediment.

Transport of sand and fine sediments from the reef surfaces have not been evaluated, but this transport is obvious to divers at the time of high trade winds when the underwater visibility is markedly reduced by suspended sand on the lee sides of coral reefs. A reduction in visibility is noted at the same times in the deeper sandy areas, as in the Sampan Channel.

Before and during World War II, the U. S. Navy did extensive dredging of reefs; their permits read that they were to dispose of the tailings on land or in deep water. Whether this was done or not cannot be ascertained at this late date. In the last several years a small hydraulic dredge has been working in various sectors of Kaneohe Bay, cutting boat channels through the shoreside reefs to homes along the shore. According to the permits issued by the Army Corps of Engineers for dredging from June 1968 to September 1969, approval was granted to remove 87,150 cu. yds. and of that 50,030 cu. yds. were to be disposed beyond edges of the reefs into the Bay. Our personal observations were that even when the dredged materials was disposed of ashore, the outflowing water carries much fine coralline material that remains suspended in the vicinity for weeks after the operation is complete.

The increased plankton biomass and its increased contribution to the sediments will be mentioned under Plankton Community, below.

The only quantitative figures on the increased rate of sedimentation in Kaneohe Bay are those of Dr. Ken Roy (personal communication and also reported in the Honolulu Star-Bulletin on 12 March 1970), in which he compared bathymetric data collected in 1882, 1927 and 1969. By careful comparison of the soundings he found no changes in depth in the first 45 years, but since 1927 there was an average decrease of 5.7 feet in the depth of the Bay from the southern basin to near the northern end of the lagoon. While the thickness of sediments deposited was not uniform, no particular pattern could be derived. Surprisingly enough, the sediments were about 75% $CaCO_3$, and only about 25% of combined terrigenous and organic origin (other than the carbonate). If the amounts removed from the reefs by dredging of the U. S. Navy were totally discharged in the deeper basins, Dr. Roy has computed that they would add only about 1 foot to the layer. The great increase in calcareous sediments in the last forty years appears to be due to accelerated reef erosion. Dr. Roy plans to publish his complete studies as an Hawaiian Institute of Geophysics, Sea Grant report.

The effects of sediments upon corals has not been well documented. Edmondson (1928) buried completely many species of Hawaiian corals and found the two dominant bay corals, *P. compresso* and *M. verrucosa* to die within 24 hours under such treatment. This, however, does not predict their reaction to a slow rain of sediment. R. E. Johannes (paper in preparation) reviews the literature on effects of sedimentation on coral and concludes: "The temporary production of turbid waters due to man's activities appears not to affect the surface reef community seriously unless siltation is so great that the biota is fairly heavily coated with sediments." However, he also points out "The exposure of reefs to brackish, silt-laden water associated with flood runoff seems to be a major cause of reef destruction historically."

Chemistry of Bay Waters

Salinity: The normal salinity of the Bay is close to that of the adjacent open ocean except during periods of excessive rainfall. Bathen (1968) reports that the salinities of the Bay paralleled his oceanic stations off the mouth of the Bay with a range of 34 $^{o}/oo$ to 35.5 $^{o}/oo$. The lowest salinity reported from any of the studies (Tseu, 1953; Piyakarnchana, 1965; Bathen, 1968) was 7.84 $^{o}/oo$ reported by Banner (1968) near a stream mouth five days after the deluge of 2 May 1965; on both 7 and 8 May most surface samples in the southern basin were below Bathan's minimum of 26 $^{o}/oo$.

Oxygen: In all studies, under normal conditions the oxygen values of the entire water column during daylight hours were close to, or exceeded, saturation values for seawater of those salinities and temperature, the values usually running between 4 and 6 ml/1. In the 24 hour stations run by Tseu, Piyakarnchana, and Bathen, there was a slight, but not serious decrease in the night hours. The only exception reported by Bathen is in the water near the sewer outfalls where the oxygen values dropped as low as 2.5 ml/1. (We are not citing the draft report of Young, Morphew, and Burbank in this report.)

Nutrients, sources: The principally studied plant nutrients, phosphates and nitrogenous compounds, are introduced to the Bay from a number of sources: two major sewage discharge lines; streams that may carry normal nutrients from the land, or excessive nutrients from agriculture or urbanization; direct land runoff; and, finally, seepage from shoreside cesspools. The amount and nature of the discharge of the two sewage outfalls have been well studied, and one study was also devoted to the streams.

In late 1962 the City and County of Honolulu opened a secondary treatment plant for Kaneohe; its outfall was located in the south-western corner of Kaneohe Bay. As the suburbs grew, the sewage collection system was expanded not only to take care of the new housing, but into the older residential areas as well. Figures for the first years of operation are not available from the City and County Division of Sewers, but they were able to give the average daily outflow in millions of gallons per day (mgd) for each fiscal year since 1964-65 (their fiscal year starts on 1 July); Piyakarn-chana (1965) gave their official figures for 1963-64; these data are presented in Table 2.

TABLE 2

Average daily discharge of sewage in millions of gallons per fiscal year from Kaneohe Municipal sewage treatment plant
(Figures from Division of Sewers)

(August, 1963)	0.71 mgd
(July, 1964)	1.10
1964-65	1.38
1965-66	1.61
1966-67	1.75
1967-68	1.99
1968-69	2.41
1969-70	2.53

The second major sewer outfall is that of the Kaneohe Marine Corps Air Station. It discharges primarily treated sewage into the southeastern corner of the Bay, almost directly opposite the municipal outfall. Gray and Lau (Draft Report) estimate that during 1970 this outfall would produce 0.8 mgd.

The amount of phosphates and various nitrogenous compounds vary with the sewage drainage area, according to Gray and Lau (Draft Report), and probably with the day or season. However, rough estimates of these amounts can be made from figures supplied by the authors on the values of raw sewage entering the Kaneohe treatment plant, and on the value found in the effluent. In Table 3, the Marine Corps was presumed to have values near that given by the authors for the raw sewage.

TABLE 3

Estimate of daily discharged total phosphate and total nitrogen, based on estimates of flow and concentrations given by Gray and Lau (Draft Report)

Treatment Plant	Av. daily discharge mgd.	Conc.total phosphate mg/1	Av.daily phosphate kg	Conc.Total Nitrogen mg/1	Av. daily total N. kg
Municipal	2.53	23.3	22	16.3	15.6
Marine Corps	0.80	20.6	6	17.1	1.4
Totals	3.33		28		17.0

The same authors estimate that from the 15,000 individuals that live in the Kaneohe Bay drainage north of the existing municipal sewage system generate about 1.35 mgd of sewage that is largely discharged into cesspools. Some thousand of these live in a new housing tract that is served by a privately constructed secondary treatment plant that discharges into the Ahuimanu Stream about one mile upstream from the Kahaluu section of Kaneohe Bay. This stream passes through a large and lush swamp on its way to the Bay, and it is quite possible that the rank grasses absorb much of the nutrients before the stream water reaches the Bay. However, Ahuimanu and Kahaluu Streams are currently being "improved" by confinement to concrete channels, so the discharge should reach the Bay in a more expeditious and concentrated manner. One would suspect that much of the nutrients discharged into cesspools set back from the Bay may be taken up by terrestrial and freshwater plants before the water enters the Bay.

No calculations have been presented of estimated discharge of shoreside cesspools which may have a more direct flow to the Bay. Similarly, no estimates have been made on the contribution of the land masses that drain directly into the Bay in times of heavy rainfall.

There is no data available, that of Young *et al*. included, that would permit the calculation of the actual average daily discharge of nutrients into the Bay by the streams, similar to that calculated for sewage outfalls above. Until such a time as the average flow of the streams and the average nutrient content of their waters has been measured, any conclusions in reference to the relative roles of the streams and the sewers in the eutrophication of the Bay must be speculative. However, an approach through simple logic may give some indication of their respective roles.

All streams carry some fertilizer salts or organic debris to the sea, for even in forests and grasslands untouched by man there are decomposible remains and their products that are flushed from the land by rains. It was this type of "pollution" that permitted the historical growth of coral in Kaneohe Bay. When the drainage basin is developed for agriculture and small town living, three sources of phosphates and nitrogenous compounds are added: pre-sewage disposal of human wastes, usually cesspools or pit latrines; livestock manure; and agricultural fertilizers, either natural or artificial. While Kaneohe was growing from 1,762 in 1940 to 14,414 residents in 1960, there was no sewage system. In the urbanization, livestock manure was decreased, the use of fertilizer changed from crop production to lawn production, but the number of cesspools vastly increased. The leakage from these into the streams must have increased correspondingly. Yet during this period there was no marked invasion of algae, at least on the middle reefs of Kaneohe Bay (see Discussion, below).

At present the streams flowing into the northern sector of the Bay pass from forest and brush lands through agricultural lands and low density housing, similar to those in the southern basin before the numerous subdivisions were created. These, then, should present no chemical contamination inimical to coral growth. On the other hand, in the southern section of the Bay, the expansion of the sewage system since 1962 should have reduced cesspool leakage into the streams, and the amounts of nutrient salts carried by them should have been reduced. It was in the period after 1962 that the greatest changes in the reefs have occurred. Therefore, it would seem that the observed changes in the balance of coral versus algae in the Bay and the death of coral upon the reefs, if associated with nutrients and not entirely caused by siltation, can be most logically attributed to the discharge of sewage from the outfalls, and not the streams.

The exception to these generalizations is the Kahaluu Stream which receives the discharge of the Ahuimanu treatment plant, mentioned above.

Nutrients, amounts: According to Leibig's "Law of the Minimum," a living organism is limited in growth and development by the parameter in its environment that is shortest in supply relative to its needs; high concentrations of other nutrients cannot stimulate growth if one is deficient. In reference to plants in the sea, these limiting nutrients may be phosphates, nitrogenous compounds, silicates, or a series of other ions that appear in trace amounts. However, the investigations to date in Kaneohe Bay have most consistently studied phosphates (as phosphate-phosphorous) and even figures for the various nitrogenous compounds are not consistently adduced in the same form. Fortunately, phosphates have been taken in many studies to be an index of pollution. Therefore, in this review the attention will be confined to phosphates.

It is unfortunate that modern techniques and equipment were not available to Tseu (1952) for her 1951 studies, for they could have established a baseline for a relatively uncontaminated Bay. However, the phosphate levels that existed at that time were below the levels of accuracy of the tests she could use. All she could state was that all values for phosphate-phosphorous during her year's study were below 0.5 μg atom/1, and that during the last four months, when she had available more sophisticated equipment, were below 0.3 µg atoms/l.

Piyakarnchana's (1965) year long study of the southern basin, which started during the first year of operation of the municipal sewage treatment plant, showed a steady increase in phosphate-phosphorous in the middle and southern portions of the southern basin, month by month. His findings are summarized in Table 4.

TABLE 4

Phosphate-phosphorous in the Southern Basin
Taken from Piyakarnchana (1965)

"Line"	Location of stations	Phosphate-phosphorous, µg atoms/l Aug. 1963	July 1964
I	3 stations to the northeast of Coconut Island	0.36	0.24
II	3 stations slightly south and east of Coconut Island	0.09	0.49
III	3 stations in southwestern corner of southern basin (near municipal outfall)	0.34	1.57

The next worker to study phosphate concentrations and distribution was Bathen (1968), who made his study from June 1966 to June 1967. He reported that the "average annual concentration" in the open ocean to be about 0.04 µg atoms/l, and that the average value for the entire Bay during his 13 months of study to be 0.32 µg atoms/l. However, he reported that the same value for the southern basin was greater than 0.60 µg atoms/l. His maximal figure of 1.43 µg atom/l, taken over the sewer outfall, was slightly less than Piyakarnchana's Line III. In his maps showing iso-phosphates for phosphate-phosphorous for 11 semi-synoptic surveys of the entire Bay, a generalized picture was shown of decreasing phosphate as the distance from the municipal sewer outfall increased, but with relatively high values extending up the lagoon towards the Ship Channel. Depending upon tide and wind, the iso-phosphates might extend as tongues, indicating diminishing concentrations towards the north, or at other times they might be in pockets of higher or lower concentration.

The detailed studies of Drs. Caperon and Cattell for 1970 have not yet been published, but through their courtesy we have been able to examine their data. They, too, show much higher values for the southern basin, and a rapid decrease in values immediately north of Coconut Island. The phosphate levels in the lagoon decrease towards the north, but they are still much higher than for open ocean. Their most interesting finding is their contrast of values reported over a period of four years at a station directly over, or near, the municipal sewer outfall. They point out that Bathen's 1966-67 mean was 1.43, the mean for Young et al. in 1968-69 at the 1 foot depth was 2.67 and their own value for 1970 was 3.94 (all in µg atoms/l). They found these three points when plotted lie almost on a straight line, and the increase in the four years was by a factor of 2.75, or of 0.75 µg atoms/l per year. To heighten the contrast, it was in this area that Piyakarnchana obtained a value of 0.34 µg atoms/l in August, 1963.

The Plankton Community

With the increased amounts of phosphates, nitrogenous compounds and other sewage-associated compounds, one would expect marked changes in the plankton community. Unfortunately we have no comparable quantitative studies on the plankton previous to the massive sewage discharges. Edmondson's (1937) work on copepods was so far removed in technique from modern studies that comparisons would be questionable. There were no more studies made until Piyakarnchana's (1965) work in 1963-64, but at that period the phosphate level was already rising; he reports that during the last six months of his study "direct significant correlations between the amount of phosphates, phytoplankton and herbivorous zooplankton were found. . . ." He warned of eutrophication of the Bay, and stated that henceforth "the bay must not be regarded as a [place to study] normal environmental conditions."

Clutter (Draft Report, revised) discusses the plankton population as he found it from July 1968 through the end of August 1969. He found that by all of his measures the plankton community showed a high productivity in the southern basin, declining as he reached his northern stations. He speculated that in the southern basin the plankton community included a larger component of nannoplankton, probably small flagellates, but he did not measure them directly. In the basin he found a low diversity of species and considerable fluctuation in population. He documents several outbreaks of "red tide" caused by extreme fluctuation in the dinoflagellate population. Apparently these "red tides" were either not extensive enough, or were not of toxic species, for no harm was done to the fauna. He reported that in a November 1969 outbreak the chlorophyll-<u>a</u> values were five times as high as the highest in his year-long studies.

Clutter also compared his figures on turbidity with those of Piyakarnchana and found "the water in both the middle and southern sections [to be] about twice as turbid in the summer of 1969 as it was in the summer of 1963." This increase in turbidity was attributed in part to the increase in the plankton.

The increase in plankton would also increase the organic sedimentation on the bottom and on bottom dwelling forms; this increase has not been measured, or at least published upon.

Clutter concludes (taken from his abstract): "Documented changes occurring in the most productive sector [e.g., the southern basin] over the past few years indicate a trend toward eutrophication, decreasing diversity, altered ecosystem structure, and decreasing plankton population stability with violent attendant fluctuations in standing stocks of a few species. None of these changes are clearly desirable, some are clearly undesirable."

The direct effects of the increase in plankton through eutrophication upon coral growth has not been studied to our knowledge. One might possibly argue that with the increase in microzooplankton, more food would be available to the coral polyps. On the other hand, the increased suspended matter including the nannoplankton that has increased the turbidity would interfere with ciliary self-cleansing of the polyps. The increase in phytoplankton itself would not provide food for the carnivorous polyps, and might well clog their capture mechanisms. The turbidity would certainly decrease the light for photosynthesis of the zooxanthellae of the corals in deeper water but this probably is not an important factor to the shallow water corals of the Bay. To our knowledge, there have been no reports on the response, or lack of response, of coelenterates to dinoflagellate toxins. In any case, almost all of the corals in the southern basin are dead (see next section), and the increase in the planktonic biomass there may have contributed to their deaths.

PRESENT STATUS OF KANEOHE BAY REEFS

During the summer of 1970 the authors became aware that major changes were occurring in the ecology of the reefs in the middle portion of Kaneohe Bay. In that section the corals of the reef were being invaded by, and in some cases, obliterated by masses of the green alga, *Dictyosphaeria cavernosa (= favulosa)* (Forskål)-Boergesen. The changes on familiar reefs were so radical that we decided to make a preliminary survey of the entire bay to discover the extent of the threat. We were unaware at that time that the proposed survey in part overlapped studies already started by Mr. James Maragos who was studying growth rates of various corals in Kaneohe Bay for his doctoral dissertation. The survey was made largely during the month of August, 1970, by the two authors; we wish to acknowledge the assistance on some of the trips of Mrs. D. M. Banner, Mr. Richard E. Brock, and Miss Lennie Muttick.

The alga grows into large coherent heads, normally several feet across. It is of dark green color, and "crunchy" in texture--rather firm, but capable of being fractured by the hands, much as a thick cookie may be crumbled. Its growth pattern often causes small hemispheres an inch or so in diameter to rise on its surface, giving the head a "bubbly" appearance (in the local press it was called the "green bubble alga"). As a head of alga grows, the surface appears to expand so that there are irregular sets of layers of the alga up to several inches thick composing the alga "body" which surrounds a central void. In this void at times remains of coral heads may be found; more commonly there is a cryptic fauna of tunicates and tubeworms. In these voids few of the usual crustaceans and worms characteristic of coral bases were found.

Methods

After the initial observations, a seven point scale was decided upon to quantify better the subjective judgment of the coral-alga relationship. The scale is given in Table 5; see also Figures 1-10.

TABLE 5

Arbitrary stages of *Dictyosphaeria cavernosa*-coral conditions used in this survey

Designation	Coral Reef Condition
0	No *D. cavernosa*, normal coral growth.
1	Slight *D. cavernosa* growth, no interference with growing coral.
2	Some invasion of coral heads by *D. cavernosa*, but not marked.
3	Heavy invasion of some or much of the coral; coral usually with tips still growing, but with base enveloped by the alga.
4	Most coral gone; that remaining heavily invaded or being overcome by the alga; most of the bottom covered by the alga.
5	Bottom either completely covered with alga, or at most with only scattered heads of coral remaining.
6	Neither living coral nor *D. cavernosa*; in most areas *D. cavernosa* replaced by mats of several other genera of algae.

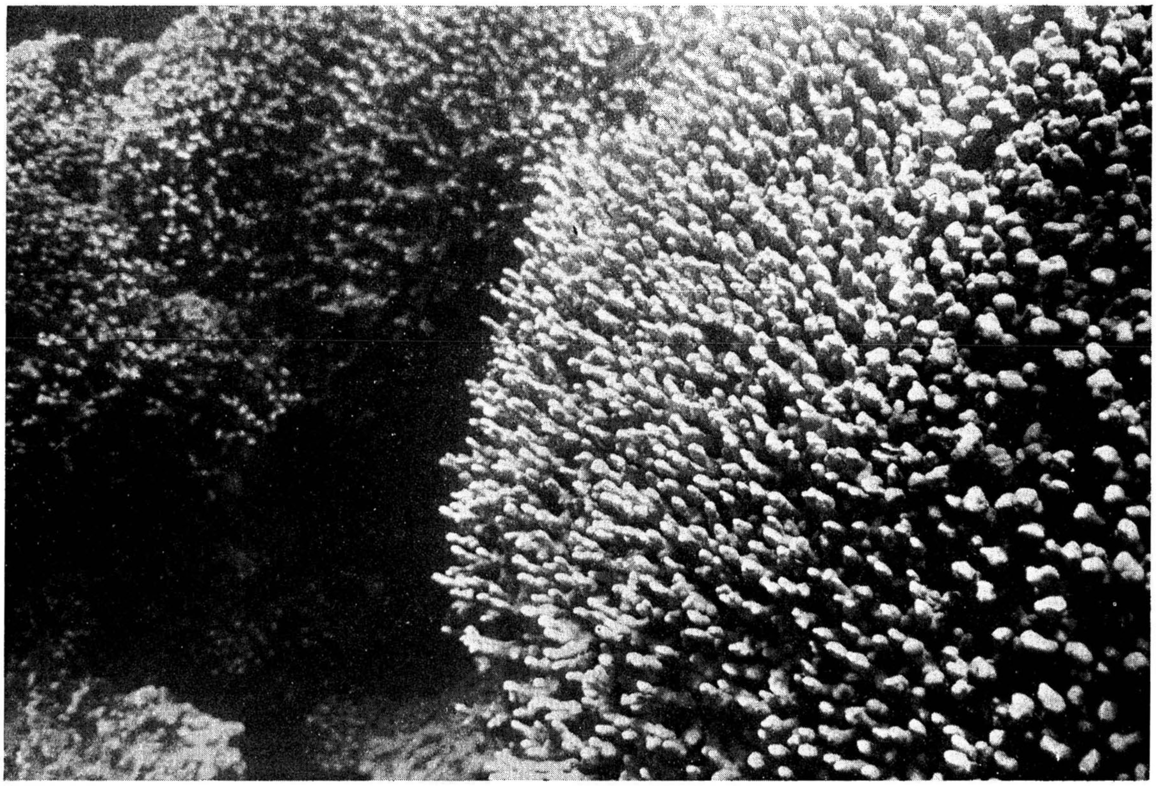


Figure 1. Bank of *Porites compressa* in normal condition, uninvaded. Condition 0. Depth about 6 feet, Station 31, windward side (compare to Figures 3 to 5 of the same reef).

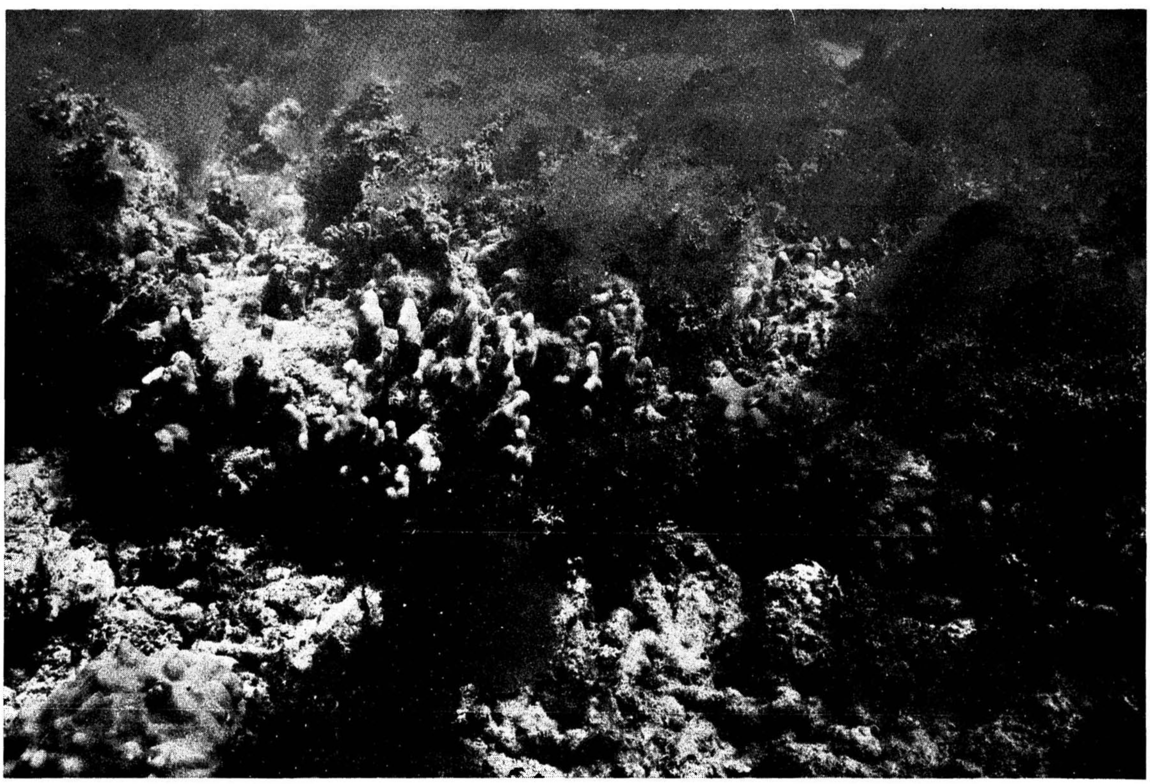


Figure 2. Small *Porites compressa* in Sampan Channel, showing other algae (including *Ulva reticulata, Sargassum spp.*) but no *Dictyosphaeria*. Condition 0. Depth about 6 feet, Station 154, area of heavy wave action.

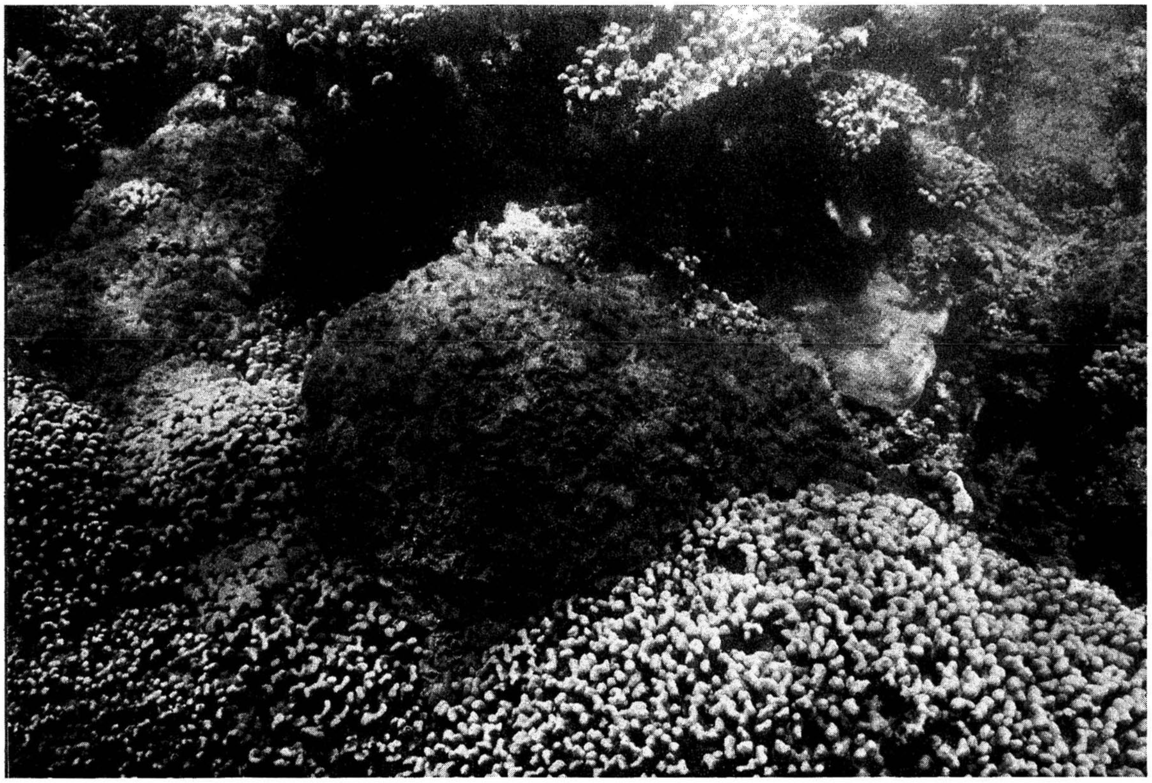


Figure 3. Large center mass of *Dictyosphaeria* beginning to invade head of *Porites compressa*; some already invaded in both left and right fields. Condition 3. Depth about 6 feet, Station 31, towards leeward side.

Figure 4. Greater invasion than in Figure 3, with central mass of *Dictyosphaeria* having eliminated some of the coral left of center, and invading the still strong head of coral right of center. Condition 3. Near Figure 3.

Figure 5. Head of *Porites compressa* invaded by "well-cropped" *Dictyosphaeria;* fingers of coral to left of center probably dissolved at base and held in position by algal mat. Condition 3. Depth about 4 feet, Station 31, leeward side.

Figure 6. ***Montipora verrucosa*** **surrounded by, but not invaded by, "uncropped"** *Dictyosphaeria.* Depth about 6 feet. Condition 4 to 5. Station 106.

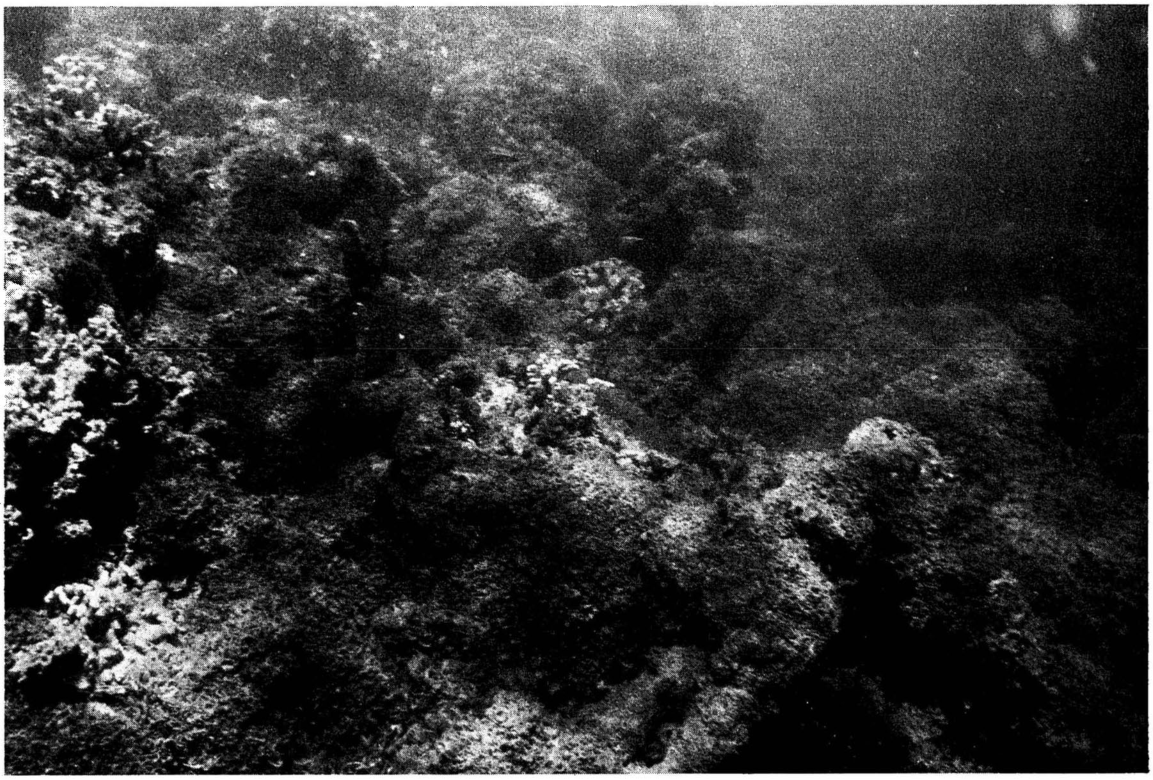


Figure 7. *Dictyosphaeria*-covered reef slope; area on extreme left dead coral rubble; living *Porites compressa* in center field. Condition 5. Depth about 8 feet, Station 43.

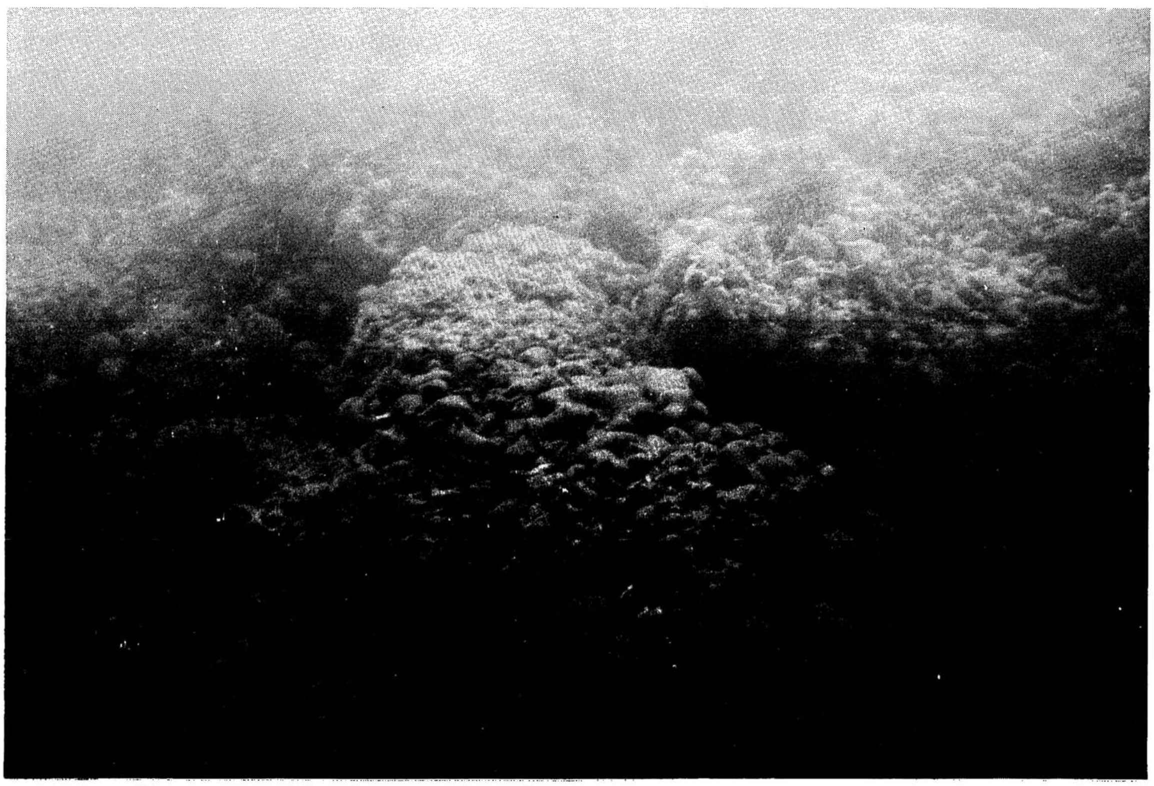


Figure 8. "Uncropped" *Dictyosphaeria* bank on dredged reef, where all *Porites compressa* has been replaced by *Dictyosphaeria*. Condition 5. Depth 10 feet, Station 137 (the suspended matter that obscures distance is characteristic of the southern basin).

Figure 9. *Dictyosphaeria* covering bottom of dredged channel; *Dictyosphaeria* largely "uncropped," with the sea cucumber *Ophiodesoma spectablis* crawling on its surface. Condition 5. Depth 10 feet, Station 106.

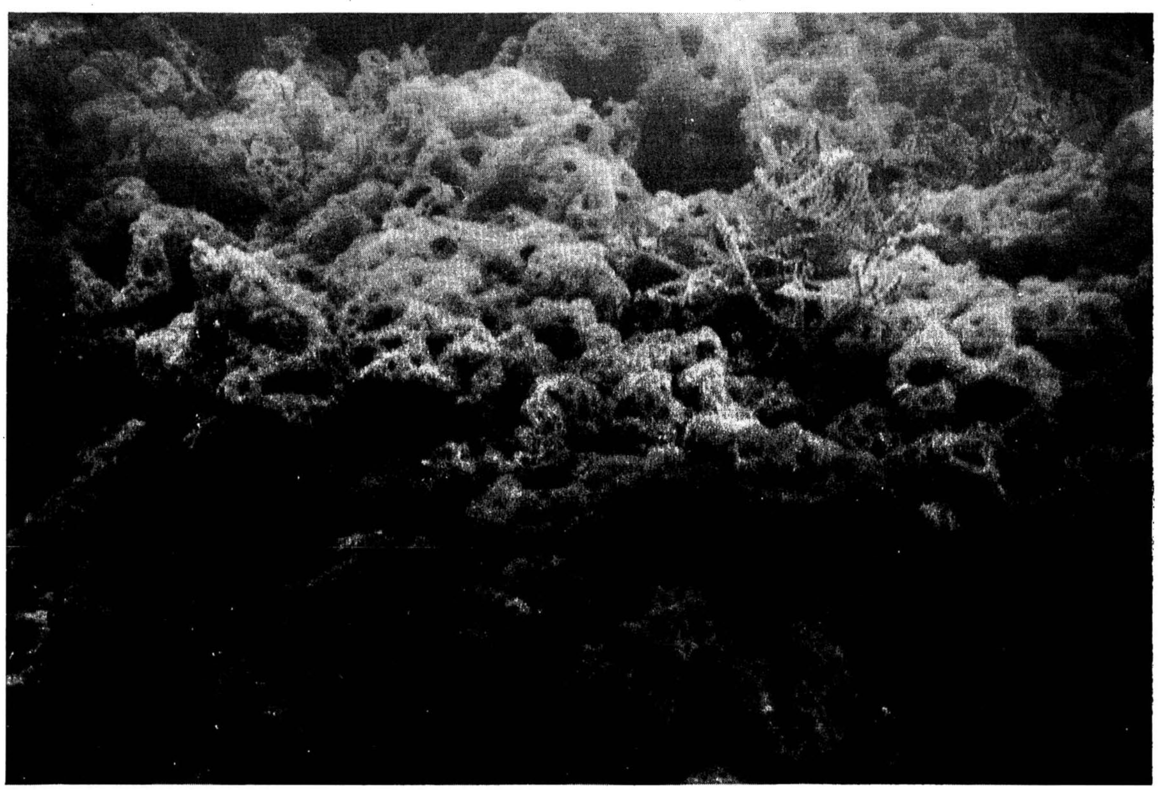


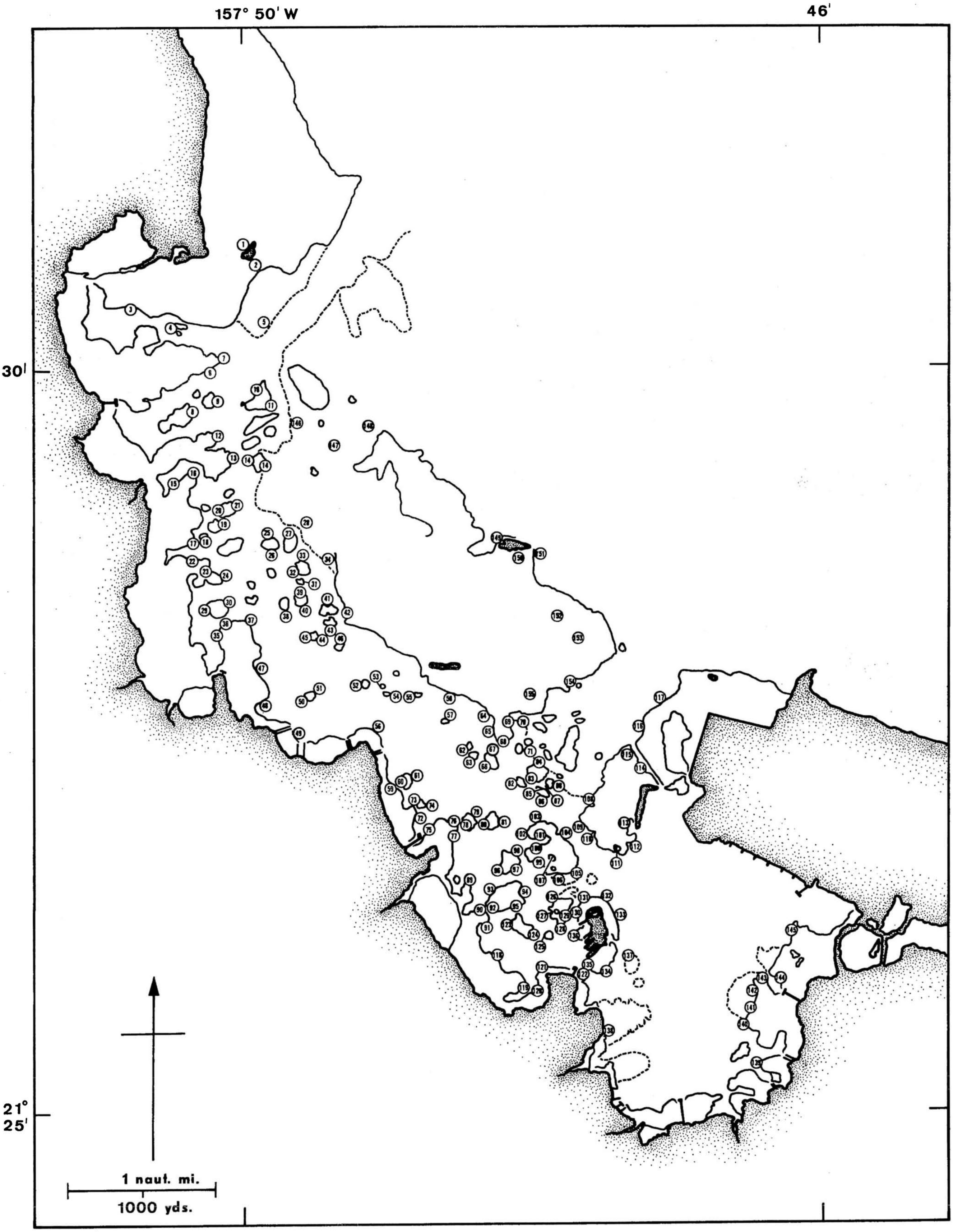
Figure 10. *Hydroclathrus* in 4 to 6 inch blanket covering an old coral reef. Condition 6. Depth 2 feet, Station 145.

The observations were largely confined to what had been once the living reef front; at some stations the outermost portion of the reef flat was also examined. Observations were made entirely by skin-diving. Usually several hundred feet of reef front was examined with dives to ascertain the depth of the lower margin of the coral or alga (depths were usually estimated but these estimated were checked from time to time by a dive gauge or by a simplified sounding line). If conditions were uniform, shorter horizontal traverses were made; on the other hand, in some areas, especially where conditions were changing, the diver would either swim or be towed for 1,000 yards or more. Often on the small "button reefs" either half or the entire circumference was examined; on many of the larger reefs observations were made in all four quadrants. In all, 155 individual areas were inspected, and the reefs along the entire coastline as well as almost all of the reefs in the Bay were visited. Fewer dives were made in the clearer outer waters of the channels and along the barrier reef as no infestations were found there. Similarly almost no dives were made along most of the inner side of the barrier reef as it is a sand slope that harbors neither coral nor *D. cavernosa*.

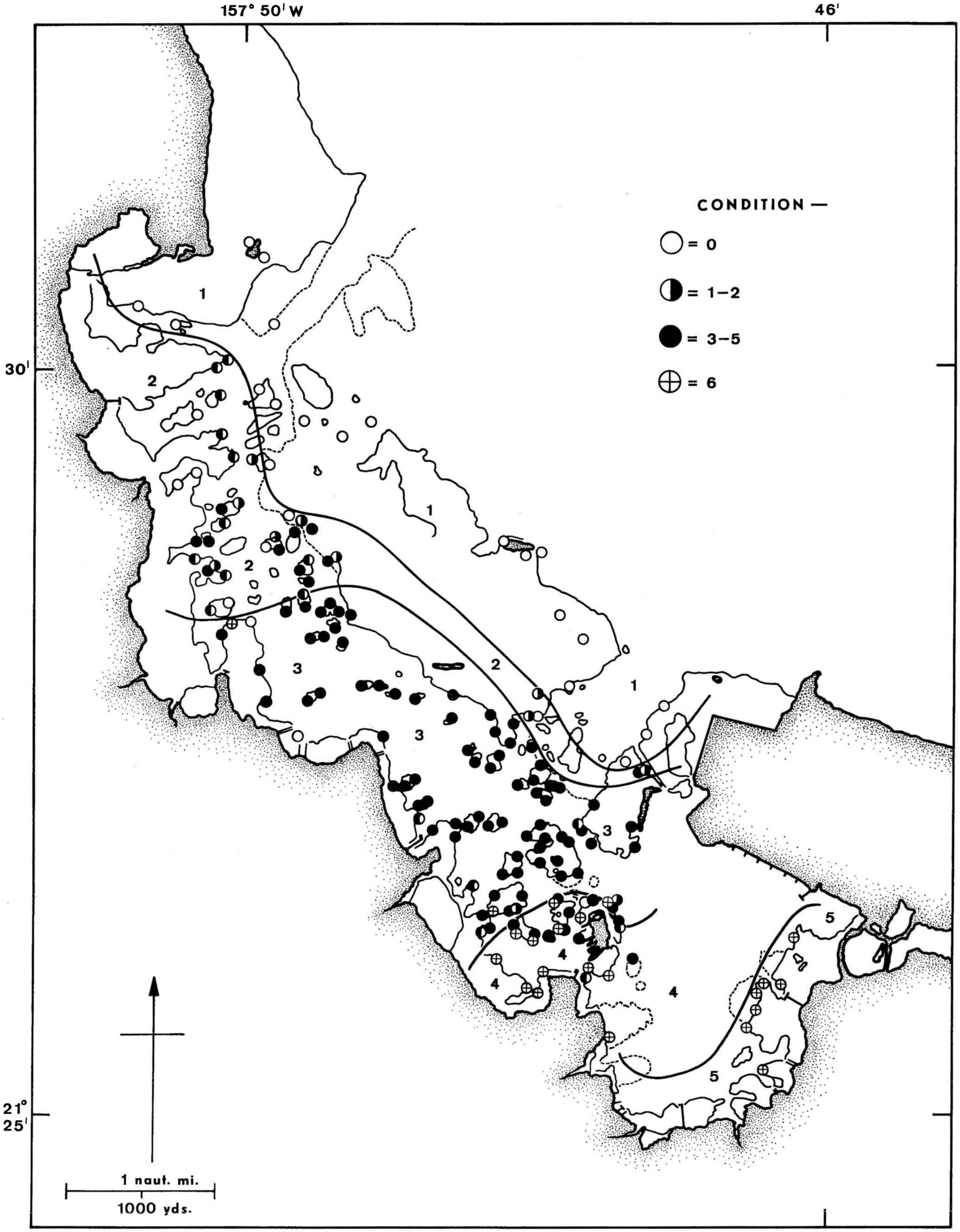
Results

The stations are located by number on Map IV (p.35) and the results are presented in Map V (p.36). A description of the observations at the stations are presented in the Appendix.

It must be emphasized, however, that conditions are not uniform from the top of the reef edge to the bottom, nor in the various sectors around a reef. An excellent example of the former is Station 109, a



MAP IV. Stations examined during survey of August, 1970; see Map V and Appendix for conditions observed.



MAP V. Degree of *Dictyosphaeria cavernosa* invasion observed. See Table 5 for description of numerical ratings. Zone 1, no *D. cavernosa*; Zone 3, heavy invasion; Zone 5, with neither *D. cavernosa* nor living coral; Zones 2 and 4, transition.

reef at the junction of the Sampan Channel and the main channel through the Bay. Here the reef top and edge, apparently slightly below low-low water, is a band about 6 feet wide of vigorously growing *Porites compressa*, without any *D. cavernosa*. On the reef flat behind this band, for about 30 feet back, *P. compressa* is being invaded by the alga, condition 3. On the reef front between 3 and 25-30 feet the alga has taken over, adjudged to be between conditions 4 and 5. In general, as with this station, shallow coral on the windward side of reefs where they would be subjected to heavy wave action would be at most only slightly invaded, but below the zone of major wave turbulence, 3 to 5 feet, the alga might be in condition 5. In the northern zone of transition (see below), some reefs are found with no *D. cavernosa* at any depth along the margin facing into the waves, but on the lee side of the same reef the alga is present in condition 3; as one swam around the reef the changing conditions could be observed.

On the basis of our findings, the Bay can be divided into three major but generalized zones and two zones of transition. In the northern end and along the open front of the Bay the coral appears to be unafflicted by *D. cavernosa* (Fig. 1). These are the sections of the bay with the greatest influx of oceanic waters according to Bathen, and are also subjected to the heaviest wave action. The dominant *P. compressa* of the inner bay is not found in abundance in this zone except to the east in the northern lagoon, near the zone of transition. The water along the Ship Channel leading to the sea is quite turbid, especially on falling tide, but as yet this turbidity seems to have had no marked effect upon the corals.

The second major zone occupies most of the middle of the Bay. Here *D. cavernosa* has invaded almost all of the reef fronts, some of which were entirely enveloped by the alga (Fig. 7). At Station 62, for example, in swimming half the circumference of the reef we found a solid blanket of *D. cavernosa* from low tide zone to about 25 feet with only one living head of coral seen. Several stations in the zone paradoxically showed only slight infestation or none; Station 49, on a shoreside reef in the middle of the *Dictyosphaeria* zone, had strong coral and no alga; at present we can offer no explanation of this lack of alga. Stations 35 and 37 in the mouth of the cove at Kahaluu are also exceptions to the pattern but in the opposite direction: there is little or no *D. cavernosa.* but few living corals also. This may be the result of the runoff of Kahaluu Stream and the silt it has carried over the years from the extensive real estate developments in its drainage basin.

The third major zone is the southern basin where neither living corals nor *D. cavernosa* were found. This is the area described by MacKay in 1915 as the "Coral Gardens" (see Introduction). In about one-half mile total that we swam along the reef front in Stations 139 to 145, we actually counted only 10 living heads of coral, 5 each of *M. verrucosa* and *P. compressa*. Most of the reef flat and edge is covered by *Acanthophora* and slightly deeper by *Hydroclathrus* (Fig. 10). These algae make mats up to six inches thick. The dead coral heads, if they were not covered by the algal mat, have heavy growths of large sponges, zooanthids, sea anemones, and tunicates.

The balance of the flora and fauna in both zones of transition are inconstant. Coconut Island lies on the southern margin of the southern transitional zone. On the eastern reef a fair amount of growing coral is found and little *D. cavernosa*, condition 2. As the northern reef is approached more and more of the alga appears below the zone of wave action, approaching condition 5. On the western side of the northern reef is found an ecological system that was not covered by our numerical system, for while the coral is dead and there is no *D. cavernosa* there is a rampant growth of sponges and mats of various reef-flat algae, mostly *Acanthophora* with extremely numerous sea cucumbers, *Opheodesoma spectabilis* Fisher. Again, on the middle of the reef due west from the island, *D. cavernosa* occurred in condition 5. However, the more western portions of the southern reef had neither living coral nor *D. cavernosa* but there were small nodules of *D. versluysii* Weber-van Bosse; living coral began to appear in scattered areas along the middle of the reef as one worked eastward.

Also perplexing was Station 137 to the south of Coconut Island (Fig. 8). This is the dredged reef mentioned in the Introduction as having a luxuriant growth of coral along its margin at the depth of approximately 10 feet. As this lies most closely to the "dead" area of Coconut Island reef which has no *D. cavernosa*, it was surprising to find the entire edge covered with a heavy growth of the alga. In a number of dives to its surface (the water was always too turbid to make observations from the surface) only one living head of *P. compressa* was found, although there were still some living heads of *M. verrucosa*. Everything else was enveloped by the alga.

In a similarly dredged area at Stations 105 and 106, the alga had attached to coral heads growing from the sand flat (Fig. 9). One separate head of *D. cavernosa* was estimated (by the body length of the diver) to be approximately 10 feet long, 6 feet wide, and 5 feet high; it may have been built by the confluence of many individual algal masses, but it appeared to be of coherent growth. In this area, as in many others, thriving *P. compressa* was found in the first foot or two below low tide level, but by the time a depth of 4 feet was reached, no *P. compressa* was left exposed.

During the brief survey, we could not tell how the alga settled or grew. Certainly its presence on slopes of dead coral rubble would indicate that it does not need living coral for its original attachment. Often heads of alga were found that seemingly were not attached to the substrate. In areas where waves could be heavy, the alga was often found detached and being slowly abraded by wave action in hollows between living or dead coral heads.

Most commonly, where attachment could be noted, it was on living heads of *P. compressa*. The initial invasion appears to be between the fronds. Where "cropping" or "grazing" (see below) was heavy, the living fingers of coral protruded an inch or more above the algal mat (Fig. 5). If these fingers of coral were seized, in most cases it was found that they were being held in position by the algal mat. The basal part of the coral skeleton, usually several inches below the top of the mat, was either chalky and friable or entirely disassociated from any basal structure. In the northern zone of transition all stages of coral invasion could be seen: first, the coral mat beginning to spread through the coral head; second, the mat complete but with the basal coral skeleton intact and all tips growing; third, where some of the normal component of tips had disappeared and the basal skeleton was either weak or gone; fourth, where only occasional living tips would appear above the algal mat; finally, where the coral had disappeared, leaving a cropped "meadow" of the alga.

Where the alga was less vigorously "cropped", the solid head of alga would grow through the outer skeleton of *P. compressa* and envelop even the tips. In several cases the outer crust of alga was broken away to reveal a blanched, but still living, branch of coral.

The interiors of *D. cavernosa* heads were not searched to determine what species of coral it had settled upon. However, in a few cases where heads were turned over and the coral skeletons were found undissolved inside, the coral was always *P. compressa*.

In the infrequent heads of *Pocillopora cespitosa*, *P. meandrina*. and *P. ligulata* found in the *Dictyosphaeria* zone, none were found to be invaded except for one head of *P. meandrina* which may have died previous to the invasion.

Montipora verrucosa also seemed largely resistant to attack, for often large heads were seen standing above a meadow of the alga, as at Stations 105, 106, and 137 mentioned above. However, in a few cases we saw what appeared to be the beginning of an overgrowth of *M. verrucosa* by the alga (see Fig. 6). Here the alga was not growing between fronds, but appeared to be in the process of actual envelopment.

The solitary coral, *Fungia scutaria*. once common on the reef edge (see Bosch, 1967), was not common where the alga had invaded. At Station 57 several individuals were found in various stages of being covered by the alga. At the reef edge individuals were found with the normal brown color from their zooxanthellae. Further down the slope several more individuals were found in the "folds" of the algal heads. One, partially exposed to light, was light brown on one side and blanched on the other; another, still alive, was totally shaded by the overgrowing alga and was almost white.

We are unable to account for a large number of dead *Fungia* at Station 75, where an estimated 75 percent of numerous individuals in several flat pockets were either dying (e.g., with dead sectors with skeleton showing, other parts alive) or completely dead. The deaths appear to have been fairly recent, for the skeletons did not bear heavy overgrowth of settling organisms. Other coral was growing in the area, and there was little *D. cavernosa*, none around the dead *Fungia*.

The growth form of the alga was perplexing. In the southern section of the *Dictyospheria* zone and in the southern transitional area the alga was often of the "bubbly" appearance, best seen in Figures 6 and 8. However, more and more frequently towards the north was the alga without the "bubbles", but presented rather a series of upstanding edges as if the hemispheres of growth had been cut off and the remaining edges healed; this is best seen in Figure 5. This difference in growth form might be the result of several factors. First, it may be that under the stimulation of higher concentrations of nutrients, the rapid growth of the alga expands the thallus into these hemispheres, while under more slow growth the thallus expands along its irregular margins. On the other hand, it may be that the hemispheres are the normal growth form under all conditions, but that these protuberances are removed either by mechanical action, as by waves or currents, or by herbivores cropping them. From our general survey, we could detect no marked difference in wave or current action between the areas of hemispheric growth and "cut" growth. We did observe schools of juvenile fish, mostly scarids, picking at or off the algae in the northern areas; these were not present in the more highly polluted southern sections. We have no evidence that these fish or other animals were actually eating the alga; they may have been picking at animals on the algal surface. As we believe that the most logical explanation of the difference in growth form is grazing by herbivores, we have referred to the condition as "cropped" in discussion. We plan to investigate the cause of this differential growth during the coming year.

DISCUSSION

Dictyosphaeria cavernosa is pan-tropical and a normal part of the Hawaiian and Indo-Pacific coral reef flora. Dr. Maxwell Doty, the senior algologist at the University of Hawaii, states that it is common enough on Hawaiian reefs as to be often a major part of the seaweed cast up on beaches after storms. He has long been familiar with its growth in Kaneohe Bay, but states that never in his experience in any part of the Pacific has he seen the alga in such massive growths as now occur in Kaneohe Bay.

As the alga is a normal part of the Bay flora and probably increased gradually to its now dominant position in the Bay, it is difficult to attempt to date the beginning of the severe stage of the invasion. It is evidently a rather recent phenomenon. Bosch (1967) remarked from 1963-64 study that "thick and smothering mats of *Dictyosphaeria*" were "present on many of the reef slopes". The spotty invasion was evidently new, for "corals found growing beneath these mats often lacked zooxanthellae". When the senior author made his survey of the Bay in 1965 to assess storm damage, the alga was not sufficiently prominent to attract his attention. No other trained biologist has remarked on its invasion in writing. However, Dr. Robert E. Johannes, returning to work at the Hawaii Institute of Marine Biology in 1969, after an absence of six years, complained about the changes on the reefs with which he had been familiar and particularly upon the invasion of *D. cavernosa*. During the summer of 1970 he found the conditions to have yet worsened. Mr. James Maragos, a graduate student in Oceanography, in planning his thesis research on the growth rates of coral within the Bay, found the alga to be an important enough factor in coral growth that he included it in his thesis plan submitted to his committee in August, 1970. Probably the best dating of the severe stages of the invasion is that of Mr. Karl Glerun who operates the glass-bottom boat in the middle region of the Bay. He states that some of his favorite reefs to show sightseers began to be "spoiled about two or three years ago [1967 or 1968]". In an attempt to preserve these reef areas for his viewers, he attempted to reclaim them by hiring boys to remove the alga by hand. His attempt was unsuccessful.

The parallel between the increase in this alga, like the eutrophication of the plankton community, with the increase in the fertilizer salt compounds is too close to appear to be coincidental. This parallel in time is possibly duplicated by a parallel in space, for the alga does decrease in the northern section of the Bay where lower levels of phosphate are found. However, this northerly decrease may also be due to increased wave actions, to more herbivores, or to the effects of other factors that we have not considered.

The best evidence of the effects of phosphates and nitrates on the growth of the alga is in an unpublished experiment that Dr. Johannes performed during the summer of 1970 while resident at the Hawaii Institute of Marine Biology. He has graciously offered his results to us for quotation:

"Five duplicate portions of a freshly collected head of *Dictyosphaeria cavernosa* were placed in two 22 L. aquaria receiving direct sunlight and seawater from the Hawaii Institute of Marine Biology seawater system, delivered at a rate of about 30 L/hr. Into one of the aquaria a nutrient solution consisting of NaH_2PO_4 and $Mg(NO_3)_2$ in filtered seawater was dripped in at a rate such that the phosphate level was increased by 2.4 µg-at/L and the nitrate level by 12 µg-at/L over ambient levels. [The laboratory seawater intake is off the southeastern edge of Coconut Island and Drs. Caperon and Cattell have maintained a sampling station about 30-50 yards away; they report (unpublished) that the phosphate-phosphorous at this station averages 0.503, range 0.268 to 1.26 µg-at/L.]

"The weight increases of the alga in the two tanks is given in Table A.

TABLE A

Increase in weight of *D. cavernosa* samples
with augmented fertilization
[Johannes' data; see text]

Control Unit		Augmented Unit	
16 July	10 August	16 July	10 August
2.85 g	3.49 g	3.49 g	5.43 g
4.65	5.19	2.83	4.85
3.60	3.71	1.89	2.94
1.60	2.23	4.35	7.26
1.68	1.93	2.75	4.71
Totals 14.38 g	16.55 g	15.31 g	25.19 g

"In the control tank the mean weight increase was 15 percent, in the experimental tank the mean weight increase was 66 percent. The difference is significant at the 0.001 level. What these data suggest is that the rapid growth of *Dictyosphaeria* presently being observed in the Bay is not yet maximal; it will grow even faster as nutrient levels continue to rise."

We are rather perplexed to try to account for the somewhat spotty distribution of the alga in both the *Dictyosphaeria* zone and both zones of transition. This was somewhat discussed under Results above. Certainly the most important single factor other than nutrients, is wave action but there must be also an interplay with currents. Possibly in the northern portions of the Bay another factor may be a spotty distribution of the herbivores which may be in sufficient numbers as to prevent any massive growth.

The dating of the death of the coral in the southern basin is difficult, but it certainly predates the reported conditions in the middle Bay. Bosch (1967) reported from his 1963-64 study on *Fungia* that "the deleterious effects of siltation are conspicuous in the southern and inner northern sectors of Kaneohe Bay where large areas of reef consist mainly of dead and silted *Porites*." In five of the eight areas he examined on the southern reefs of the Bay he found no *Fungia*. In his 1965 survey the senior author found living coral along the entire southern reef front, but even at that time they were not vigorous and did not present the usual "living wall" on the front. Perhaps the death of the coral in this section has been gradual over many years, and may well have started when the U. S. Navy did its extensive dredging in World War II; as pointed out, the old "Coral Gardens" were dredged at this time.

It is certain that the conditions in the southern bay are inimical to the settling and growth of coral, for no new young colonies were seen in the southern stations. The most telling evidence is that of Mr. James Maragos, as related in his signed article in a Honolulu newspaper (Honolulu Star-Bulletin, 25 September 1970, p. D-1; other data not available. Quotation with the permission of the Honolulu Star-Bulletin):

"I also carried out growth studies on corals in the bay.

"Colonies of the six most abundant species of corals were collected, transplanted, and anchored to metal platforms placed in 25 different locations within the bay.

"Among the corals used was the dominant finger coral, Porites compressa. (See photo). [Photo from article not reproduced].

"This coral contributes over 90 percent of the total mass of living corals in the bay.

"Yet when finger coral was transplanted to the six southern bay stations, all died within a short period of time.

"These experiments were repeated seasonally, for one year with the same results.

"Of the five other species of corals used in the area, two died quickly, two survived but were in poor health or failed to grow, and only one species survived and grew, although it displayed abnormal growth forms."

As has been noted, *D. cavernosa* was found in only one of the stations in the southern basin, and it was not plentiful in southern transitional zone. Analysis of the factors restricting its growth have not been made, but certainly its lack on the northwestern side of the Coconut Island reef cannot be attributed to wave action, for this area lies on a protected channel and the reef opposite has heavy growth of the alga.

The death of the coral and the lack of invasion by *D. cavernosa* on the southern basin may be related. It is possible that siltation is heavier there and is inimical to the growth of both coral and the alga, or it may be that some as yet unknown factor in the sewage discharge, such as the chlorine put in to sterilize it, or an herbicide or a pesticide it may carry, is the active agent suppressing both. On the other hand, the abundance of phytoplankton together with other suspended material in the southern basin may be clogging the coral polyp's ciliary cleaning and feeding mechanism, while *D. cavernosa* may be unable to compete with other alga in the more highly fertilized waters. Answers to these problems will have to await more detailed studies.

We have not determined the role of the alga as an available primary producer in the Bay. As indicated in the foregoing section, the difference in growth form between the north and south portions of the *Dictyosphaeria* zone may be caused by unknown herbivores cropping the alga. We also indicated that we saw juvenile fish picking at the alga, whether at the plant or attached animals we do not know. We have also seen the sea urchin, *Tripneustes gratilla* (L.) on the alga, and eating the alga in laboratory aquaria. However, *T. gratilla* is not common in the quiet water where *Dictyosphaeria* is abundant. We have been told that a certain sea cucumber prized for food is found at night on the alga, but night search in several restricted areas showed no herbivores whatsoever on the alga.

The ecological effects of the replacement of coral by *D. cavernosa* will probably be profound. Where other ecological conditions are right, its heavy growth should develop a larger population of those herbivores capable of eating it. However, as a balance between the grazers and the algal growth has not yet been achieved in the years of its abundance especially in the southern lagoon area, it may be that the herbivores cannot tolerate the conditions under which the alga thrives. On the other hand, those animals either associated with the tips of the coral, as the young of the fish *Dascyllus albisella* which use the coral for hiding, or the numerous species of shrimp, crabs, worms, etc. normally found in the base of the branching coral, will be without a habitat. Those carnivores, both fish and invertebrate, that normally feed on coral-associated animals will be without their food sources. The cryptic fauna, found in the voids within the heads of *Dictyosphaeria*, is not normally available for these carnivores.

An actual physical destruction of the reefs can also be expected, for where the softer alga has replaced calcareous rampart of growing coral, storm waves can be expected to erode the reef edges away. This, incidentally, will cause more silt in the waters of the Bay. Mr. Karl Glerum has reported such erosion in some of the areas that he previously used for viewing from his glass-bottomed boat.

CONCLUSIONS

We have presented evidence of the great change in the coral reefs of the central and southern sections of Kaneohe Bay on the Island of Oahu over the last 50 years and particularly over the last 10 years. We have found the coral on the reefs in the southern basin to be almost entirely dead, and that in the central portions of the Bay to have been invaded and in many places replaced by the alga, *Dictyosphaeria cavernosa*. We have also presented evidence from others on the increased freshwater runoff, increased siltation, and increased volumes of sewage during especially the last 10 years. We have reported from these sources indications of the eutrophication of the plankton community. From these data we suggest that the major ecological shift in the benthic reef fauna is the result of these four factors, which in turn is the result of urbanization of the Kaneohe Bay watershed.

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[3]These "Draft Final Reports" were issued in a mimeographed and bound form in June, 1969, by the Water Resources Research Center of the University of Hawaii. They have had "controlled circulation" in the interested scientific and governmental circles and some of their data and conclusions have been cited in both the public press and on public forums. However, we regard them as privileged communication and all quotations and figures taken directly from them have either been submitted to the author or to the Director of the Center for approval of our use in this paper.

APPENDIX

Station Notes From Survey

(D. = *Dictyosphaeria cavernosa;* P. = *Porites compressa;* M. = *Montipora verrucosa;* V. = Estimated underwater visibility)

Station Number	Date	*Dictyosphaeria* condition	Notes
1	8/20	0	3 ft. deep, with strong waves.
2	8/20	0	6-8 ft. deep, with strong waves.
3	8/18	0	Muddy bottom, no live corals; V.=6'.
4	8/18	0	Patch of coral of fair growth; V.=5'.
5	8/18	0	Depth about 12', moderate growth of coral, mostly *P. lobata;* strong wave action; V.=6'.
6	8/18	2	Some protection from waves; V.=5'.
7	8/18	2-3	Vigorous coral growth; stronger wave action than station 6.
8	8/18	0	Vigorous coral growth, windward side of reef; V.=10'.
9	8/18	2	Good coral growth, leeward side of outermost reef; V.=10'.
10	8/18	0	Near Buoy 11, coral rubble bottom; V.=15'.
11	8/8	0	Coral at 6-8'; good growth.
12	8/18	1-2	D.=1 on windward, 2 on leeward; both sides with good coral growth; V.=8'.
13	8/8	1	Good coral growth; area facing waves.
14	8/8	0-2	D.=0 on windward, 2 on leeward; both sides with good coral growth; V.=15'.
15	8/18	0	Moderate coral growth; V.=4'.
16	8/18	0	Moderate coral growth; V.=6'.

Station Number	Date	*Dictyosphaeria* condition	Notes
17	8/17	3-4	Patchy, with some good P. to 20'.
18	8/17	0-3	Halfway around a 100' patch reef; 0 on windward side, 3 on leeward side; V.=6-8'.
19	8/17	1	Reef flat with some D.; V.=4'.
20	8/17	3	Good coral growth; V.=6'.
21	8/17	1	Windward side, rubble bottom, little coral or D.; D. not "cropped"; V.=6'.
22	8/17	1	Moderately vigorous coral; V.=8'.
23	8/17	1-3	Good coral growth; D.=1 on windward, 3 on leeward side; D. "cropped"; V.=10'.
24	8/17	2	Vigorous coral, D. below 2', well-cropped; V.=8'.
25	8/20	1-3	Reef 10-20' deep; D.=1 on windward, D.=2, 3 on leeward; V.=25'.
26	8/18	0	Same reef as 25, but on channel side with strong wave action; V.=25'.
27	8/20	0	Vigorous coral at 6-8' deep in patches; V.=25'.
28	8/20	0-3	Towed about quarter-mile over reef at 10-20' depth from north end with neither P. nor D. to south end with vigorous P. and D.=3; V.=25'.
29	8/17	1	One head of D.; smaller P. heads above 6', larger below; V.=6'.
30	8/17	0	No live coral on reef flat, vigorous coral on slope; V.=6'.
31	8/20	2-4	Good coral, D. spotty, some "cropped", some "uncropped".
32	8/20	3-4	Leeward side, D. "well-cropped"; V.=25'.

Station Number	Date	*Dictyosphaeria* condition	Notes
33	8/20	0-1	Deeper reef, ranging from 6-20' deep; vigorous coral growth, D.=1 on flat, 0 on edge; V.=15'.
34	8/20	2-3	Reef at 10' deep, good coral, D. "well-cropped"; V.=20'.
35	8/17	3	Much sediment, D. common above 2', no live coral above 6', below scattered small living heads; V.=6'.
36	8/17	6	Only scattered small heads of living coral; V.=3-4'.
37	8/17	0	Moderate coral growth; V.=6'.
38	8/18	4	D. in places growing on rubble; coral being encroached.
39	8/18	1-2	Leeward side of reef; V.=15'.
40	8/18	2-3	More D. visible than coral, "well-cropped"; V.=12'.
41	8/8	2-5	D.=2-3, windward, D.=5 in areas on leeward; "cropped"; V.=10'.
42	8/20	2-4	D.=2-3 above 6', below 6', 4.
43	8/20	5	Almost complete cover of D., "cropped".
44	8/20	5	Same as 43; V.=25'.
45	8/20	4-5	Leeward side; some patches "uncropped".
46	8/20	5	D. almost complete cover; 2 living coral in half circumference of button reef.
47	8/17	0-3	D. and coral spotty in occurrence, D. "well-cropped"; V.=10'.
48	8/17	0-3	Same as 47.
49	8/17	0	No D.; vigorous coral; V.=15'.
50	8/20	2-5	Leeward side: Shallow, D.=2; below 3' D.=4-5; M. uninvaded.

Station Number	Date	*Dictyosphaeria* condition	Notes
51	8/20	2-5	Windward side, same as 50.
52	8/20	5	V.=25'.
53	8/20	5	D. only slightly "cropped".
54	8/20	5	D. "cropped"; V.=25'.
55	8/20	5	D. only slightly "cropped", reaching to sand bottom at 25'; V.=20'.
56	8/17	5	D. covering from 3' to 20' deep, mostly "cropped"; V.=15 '.
57	8/21	5	D. surrounding button reef except for leeward sand and rubble slope, not heavily "cropped"; V.=20'.
58	8/21	4	Much rubble without D.; not "well-cropped"; V.=15'.
59	8/16	4	D. "well-cropped", some living coral.
60	8/16	5	D. extending to bottom at 25', "well-cropped".
61	8/16	5	D. "well-cropped".
62	8/21	5	D. to 25'; one living coral in half circumference of button reef.
63	8/21	5	D. a uniform cover in deeper water, new invasions at reef edge.
64	8/21	4-5	D.=4 from reef edge to 5', 5 from 5' to 25', not heavily "cropped"; V.=20'.
65	8/21	2-4	D.=2-3 to 3', 4 from 3' to 20', "well-cropped"; vigorous coral at upper edge of reef front.
66	8/21	3-4	No live P., scattered clumps of D.
67	8/21	3-4	Same as 66, D. to 25', little "cropping"; V.=20'.
68	8/21	2-5	(Towed from 68 to 69) Fair P. growth below 5'; D.=5 in patches; V.=15'.

Station Number	Date	*Dictyosphaeria* condition	Notes
69	8/21	1-5	In a cove-like pocket: D. gradually changing on west side from 5 on slope, 4 on flat to 1 on east side; vigorous coral growth; V.=25'.
70	8/21	0-3	Towing eastward: bottom changing from good P. and sand with D.=2-3, to rubble with D.=0.
71	8/21	4	Reef at 8'; most scattered P. engulfed.
72	8/16	1	Good coral growth.
73	8/16	3	D. heavy and "well-cropped" below 6'; scattered living coral.
74	8/16	3	Same as 73.
75	8/16	3	Same as 73. Pockets of dead or dying *Fungia*.
76	8/16	3	Little living coral, and that being encroached upon.
77	8/16	4	D. extending from 2' to 20', engulfing coral, not heavily "cropped".
78	8/21	4	Leeward side: D. reaching 30'; V.=10-15'.
79	8/21	5	Windward side: D. in almost solid cover.
80	8/21	5	D. in solid growth except for rubble slope.
81	8/21	5	Upper 5' rubble, little D.; below, D. almost continuous.
82	8/21	5	No coral visible, large masses of D. "well-cropped".
83	8/21	(4)	Bottom mostly rubble, sand and *Sargassum*, only 3-4 heads of P., all of which had D.

Station Number	Date	*Dictyosphaeria* condition	Notes
84	8/21	2-3	Windward side of reef: scattered P. at 5'-15', some invaded by D.; D. "well-cropped"; V.=10-15'.
85	8/21	5	In upper 5', *Acanthophora* dominant; below, D.=5, reaching to 25'; V.=10-15'.
86	8/21	4	Mostly rubble slope with few corals; large patches of D., "well-cropped"; V.=10-12'.
87	8/21	5	Leeward side: *Acanthophora* dominant above 3', no live coral; D. covering 35-50% of slope.
88	8/21	4	Rubble bottom, most heads of P. invaded. No invasion of *Pocillopora spp.*, some "cropping".
89	8/16	2	Good coral growth. D. "well-cropped".
90	8/16	3	Scattered coral, some engulfed; D. "cropped".
91	8/16	2-3	Scattered heads of D. "well-cropped", no P. or D. in upper 2' of reef front.
92	8/16	6	Scattered heads of coral, some *Acanthophora*.
93	8/22	0-5	Rubble slope; some P. uninvaded in upper 3'; where conditions permitted, D. continuous from 3' to 12'; heavy and dying *Acanthophora* in pockets; V.=10'.
94	8/22	3-5	Some invaded but living P. above 3'; below, massive growth of D. "uncropped" to 20'; V.=8'.
95	8/22	2-3	Fair growth of young P. and M.; D. not uncommon, but not invading all heads; D. reaching to 12'; V.=10-12'.
96	8/22	3	Mostly rubble, coral in spots; D. patchy, mostly "well-cropped"; V.=12'.

Station Number	Date	*Dictyosphaeria* condition	Notes
97	8/22	3-5	At reef edge, D.=3; at 6', D.=5; moderate "cropping"; V.=10'.
98	8/22	4-5	At reef edge to 4', D.=4; D.=5 from 4' to 25'.
99	8/22	5	D. invading reef flat for 15' and down slope to 30'; *Acanthophora* and *Hydroclathrus* in pockets; V.=10'.
100	8/22	5	D. invading reef flat to 15', reef slope to 25', "well-cropped"; V.=15'.
101	8/22	5	Same as 100.
102	8/22	5	Upper 4' with less D.'; D. extending to 30'; V.=15'.
103	8/22	4-5	D.=5 in deeper water, extending to 20'; V.=12'.
104	8/8	3-5	Swimming traverse along windward side and into small cove; D.=5 on windward side, except top edge; D.=3 in cove; V.=12'.
105	8/22	2-5	No invasion of reef flat, at edge some uninvaded P.; below 5', solid bank of D., on slope and extending out on dredged sand bank at 10'; not "cropped"; some M. being enveloped; V.=12'.
106	8/22	2-5	Slope mostly rubble; some P. uninvaded; on dredged platform, all P. enveloped; D. not "cropped"; V.=8-10'.
107	8/22	4-5	Pocket in reef: D.=4 at margin, 5 on slope extending to 15'-18'.
108	8/8	3-4	D. with some "cropping"; V.=10'.
109	9/7	0-5	Reef flat invaded, condition 3, for 30'; crest of reef edge vigorous P. without D.; D.=5 on reef slope, to 30', "well-cropped"; V.=6-8'.
110	9/7	4	D. to 25'-30', "well-cropped".

Station Number	Date	*Dictyosphaeria* condition	Notes
111	9/7	4	Pocket in reef front; east side D. and masses of *Acanthophora*, west side, D. only, extending to 20' (depth of pocket); "well-cropped"; V.=6-8'.
112	8/8	5	D. in massive growth below wave zone.
113	8/12	5	Protected pocket; D. covering coral; some slopes of sand; V.=8'.
114	8/8	2-3	Heavier growth along inner, more protected parts of channel; V.=15'.
115	8/8	0	Area of strong wave action.
116	8/1	0	Same as 115.
117	8/1	0	Same as 115.
118	8/16	6	Estimated quarter of coral alive. No conspicuous algae.
119	8/16	6	Less than quarter of coral alive. No conspicuous algae.
120	8/16	6	Few living coral, 2 heads of D. seen; V.=4'.
121	8/1	6	No living coral, no D.
122	8/16	1-2	About 25% coverage with living P. and M.; no conspicuous algae; V.=3-4'.
123	8/22	3,6	Leeward side: little and scattered living coral; D. also scattered, some massive growths; V.=8-10'.
124	8/22	4,6	Windward side: Only 1 small head living M. seen, no P.; D. vigorous but scattered; sponges and zoanthids common; V.=6-8'.
125	8/22	5	Swam half circumference of button reef: no live P., few living M.; D. discontinuous, reaching 25'; V.=8'.
126	8/22	3,6	Small heads D. on dredged flat at 10';

Station Number	Date	*Dictyosphaeria* condition	Notes
126 cont'd.			on gradual slope *Acanthophora* in continuous growth; a few living heads of P., uninvaded; V.=12'.
127	8/22	2,6	Only 3 patches of D., widely scattered heads of living coral; *Acanthophora*, sponges, hydroids abundant; V.=8'.
128	8/22	3,6	One living head of coral; D. in patches, more abundant towards point; little *Acanthophora*, numerous hydroids and sponges.
129	8/12	5	D. massive below wave zone; V.=8'.
130	8/22	6	No D., almost no live coral, patches of *Acanthophora*, sponges abundant; V.=10-12'.
131	8/22	5	D. carpeting from reef edge to 20', "cropped" in shallower water; D. also in pockets on reef flat; living coral on reef edge.
132	8/22	2-5	D.=2 at start, reaching condition 5 on NNE side, extending below 15'; some living coral on reef edge.
133	8/16	2-4	D. patchy, some live coral.
134	8/16	6	Almost no live coral on south side, improvement towards southeast.
135	8/22	6	Almost all coral dead, numerous sponges; no D.; V.=8-10'.
136	8/22	5	Continuous D. cover from 2'-20', little live coral at reef edge; V.=10'.
137	8/16	5	Reef dredged to 10', D., a solid blanket along edge and "uncropped"; inner parts sand; free heads of living M. not infrequent; V.=6-8'.
138	8/16	6	Scattered P. below 4'; no D. or other algae; numerous zoanthids, anemones and sponges; V.=3-4'.

Station Number	Date	*Dictyosphaeria* condition	Notes
139	8/16	6	1 living head of each P. and M.; no D. or other algae; sponges, sea anemones common; V.=6'.
140	8/16	6	4 living heads of coral; *Hydroclathrus* common in protected locations, *Acanthophora* in more exposed areas.
141	8/16	6	No coral or D.; algae as 140; numerous sponges.
142	8/16	6	As 141; *Acanthophora* invading dredged platform at 10'; V.=8'.
143	8/16	6	4 living heads of coral, no D., less *Hydroclathrus*, probably due to wave action.
144	8/16	6	No coral, no D.; *Acanthophora* above, *Hydroclathrus* in a thick blanket below about 3'; sponges, anemones, worms, tunicates abundant on exposed dead coral; V.=3-4'.
145	8/16	6	As 144.
146-148	9/7	0	Points on reef northwest of Kapapa Island: heavy wave action and rubble bottom at 8'-15'; wave resistant algae (*Sargassum*, etc.); no D.; few corals; V.=30-50'.
149-151	8/23	0	Three areas about Kapapa Island, all with heavy wave action: mostly rubble and "bedrock"; some coral and algae, no D.; V.=30-60'.
152	9/7	0	Largely rubble bottom at 6'; one large head of *P. lobata* partially invaded with mixture of algae, probably in a previously killed area; V.=20-30'.
153	9/7	0	Scattered dives behind breaker zone in 6-10' of water. Largely rubble zone; *P. lobata* scattered; no D.; V.=20-30'.
154	9/7	0	Scattered coral including P. at about 6'; several genera of algae but no D.; V.=20-30'.

Station Number	Date	*Dictyosphaeria* condition	Notes
155	9/7	1-2	Heavy growth of P. 1-3' deep, D. not common, "well-cropped"; V.=15-20'.